The Effects Of Color To The Eye And Its Importance For Heliport Lighting

A Thesis
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Master of Science
Degree
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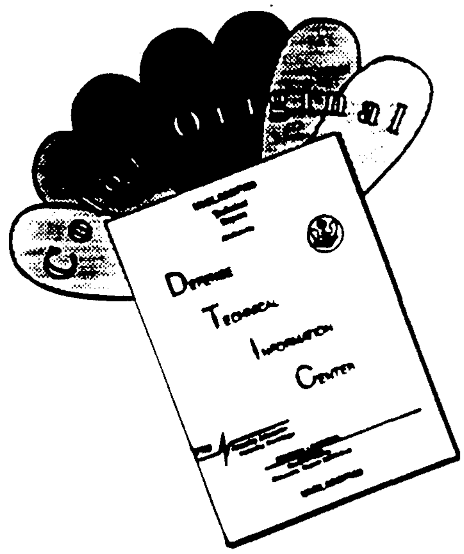

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DEDICATION

This thesis is dedicated to my wife

Lorraine Colleen Ernst

for her love and support while I journey to achieve my dreams.

To the Graduate Council:

I am submitting herewith a thesis written by Craig Allen Ernst entitled "The Effects Of Color To The Eye And Its Importance For Heliport Lighting. I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin

Ralph Kimberlin, Major Professor

We have read this thesis and
recommend its acceptance:

Charles T.N. Paludan

Frank G. Collins

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

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Lastly, an unfeigned thank you to the lighting manufactures who donated equipment and supported this research during testing. A very special thank you to Lite Beams Inc. whose contributions were pivotal to the success of this research.

Abstract

The objective of this thesis is to determine the optimum color for heliport approach lighting. Changes in air navigation from terrestrial based navigation aids to satellite based navigation aids will provide heliports with a precision instrument approach capability never realized before.

This advancement in air navigation has created a requirement for better heliport approach lighting systems. By studying the physiological and psycophysical capabilities of the eye and it's imperfections, a scientific selection of color that enhances the eye's performance can be achieved.

The results of field testing, using an experimental helipad, has shown that light at a wavelength of approximately 525 nm (green-blue) could very well be the best color for heliport approach lighting systems.

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Chapter 1

Introduction

Purpose

The space based aviation navigation system that will be in operation by the year 2000 will bring tremendous enhancement to the air transportation system in the way of instrument flight, particularly for helicopters. The helicopter industry has never had a true heliport to heliport instrument flight rules (IFR) capability. The ability to operate in adverse weather conditions is very important to the helicopter industry especially for operations such as Emergency Medical Service (EMS). " The advent of the Global Positioning System (GPS) with its ability to allow accurate navigation at any altitude without reliance upon ground based equipment has been a breakthrough for helicopter infrastructure." (Kimberlin, 1995). The accuracy improvement of this GPS based system will allow helicopters to fly precision instrument approaches in adverse weather conditions to roof top heliports.

All precision instrument approach systems are required to have an approach lighting system to facilitate the safe termination of flight. Some approach lighting arrays are so effective in providing visual terminal guidance in poor weather conditions that the visibility requirements to execute the instrument approach can be lowered. The navigational precision that the new GPS based navigation system provides brings with it the requirement for better approach lighting systems. This thesis will show that the design of

future heliport approach lighting systems must consider the color of the light as part of the design criteria.

While searching for information on this topic it became obvious that little, if any scientific research has been conducted on the color of light used in aviation lighting arrays, and whether or not they can be optimized to enhance a pilot's visual performance. There is now sufficient scientific knowledge of human color vision to show that color lighting can have an adverse effect on a pilot's vision based on the physiological shortcomings of the eye. The purpose of this thesis is to propose that retinal physiology pertains to color selection of heliport approach lighting based on research and experimentation performed in this area, and to determine the optimum color for heliport approach lighting.

Background

The Federal Aviation Administration (FAA) is studying the necessary requirements for a helicopter airway infrastructure in an effort to maximize the potential of the helicopter as a short haul transportation system. The University of Tennessee Space Institute (UTSI) is part of this initiative and has conducted research on heliport lighting systems for GPS precision approaches.

Historically, it appears that aviation color conventions have been inherited from several sources. Red and green navigation lights come from maritime practice; and green for go, red for stop comes from early railway practices (Watkins, 1971). George Godfrey, president of the Aerospace Lighting Institute, believes that the FAA has never scientifically investigated

the effects of color with respect to human visual response (Godfrey, 1996). Most of the lighting specifications required by the FAA are based upon tradition and international agreements, not upon the science of the physiology of the retina of the eye, which is of paramount importance in making such selections (Schmidt, 1996).

Currently, there are few heliports that have a precision instrument approach capability. However, the new aviation navigation system will give every heliport in America a precision instrument approach capability. Additionally, because helicopters can fly instrument approaches at slower airspeeds and greater approach angles than fixed wing aircraft, operations at lower weather minimums are possible. Under these conditions where the pilot is breaking out of the weather at low altitudes, an approach lighting system must be visibly superior than the surrounding environment so that the pilot can quickly acquire the heliport and conduct a safe visual approach and landing. By selecting the proper color, visual acquisition times can be reduced.

The heliport environment is drastically different than the airport environment. Geographical locations vary from helipads on top of skyscrapers to easily accessible helipads in open rural areas. They each pose different challenges, such as limited space to install the lighting array, and whether or not the background lighting contrasts with the approach lighting. Most will agree that the worst environment for a heliport lighting system is a heliport located downtown in a city. The effects of the surrounding city lights can make the heliport lighting difficult to see and could induce visual perception problems if the proper color is not employed. It is important that the color

used contrasts positively with the background lighting to make the heliport extremely visible to the pilot. The amber color lighting currently used for heliports is washed out, to some degree, by the yellow hue of the sodium lights typically used in cities.

Heliports are likely to be built in areas where the amount of real estate is limited, forcing the designer to build a compact approach lighting system as compared to the very large approach lighting systems used at airports. This challenge demands that every possible factor must be considered when designing future heliport approach lighting systems so that the proper visual information is provided to the pilot. The geometric form of the lighting array coupled with the proper lighting color are the two most important factors that will provide this critical visual information.

Chapter 2

Sight & The Eye

Aviators rely more on sight than any other sense to orient themselves in flight. During the day or at night, under Instrument Meteorological Conditions (IMC) or Visual Meteorological Conditions (VMC), vision is the sense that makes aviators aware of the position of their aircraft in space.

The eye is a wondrous optical instrument designed to transform less than one millionth of one percent of the measured electromagnetic spectrum, (visible light), from a stream of photons to a focused image and finally to neural signals. The electromagnetic spectrum is illustrated in figure 1. The tissues of the eye are highly specialized and some of the most complex in the body. No other organ in the body integrates so many different tissues in one system like the eye. One example of this is the cornea. It is special in that it has no blood supply. In essence the cornea is separate from the rest of the body, which makes possible cornea transplants because antibodies will not infiltrate the cornea and cause rejection.

In order to understand some of the physiological effects of color on the eye, a fundamental understanding of the anatomy of the eye is needed because our perception of color, and its effect on our visual and neural systems, begins as light enters the eye. An illustration of the eye's structure is provided in figure 2.

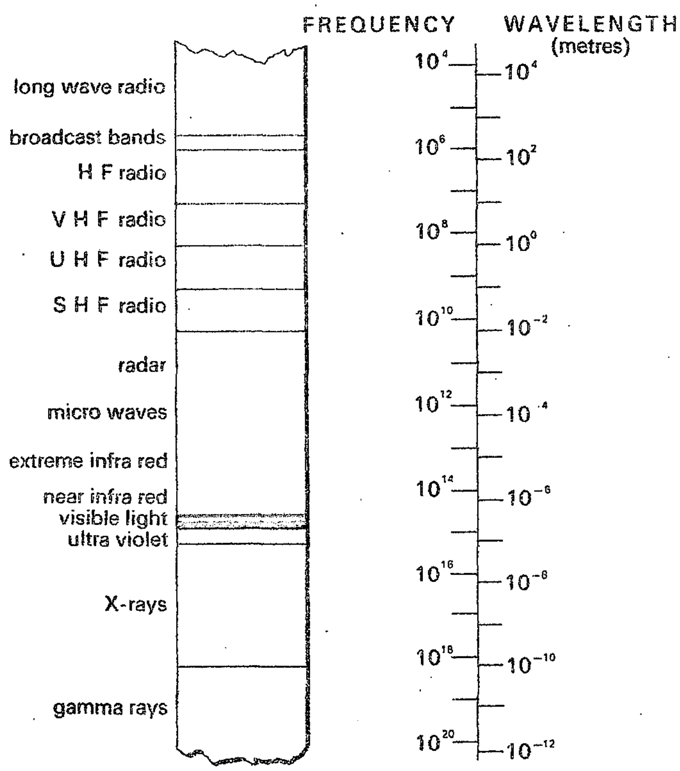


Figure 1. The Electromagnetic Spectrum

Source: R. L. Gregory. Eye and Brain; the psychology of seeing. New York: McGraw-Hill. (1966), 21.

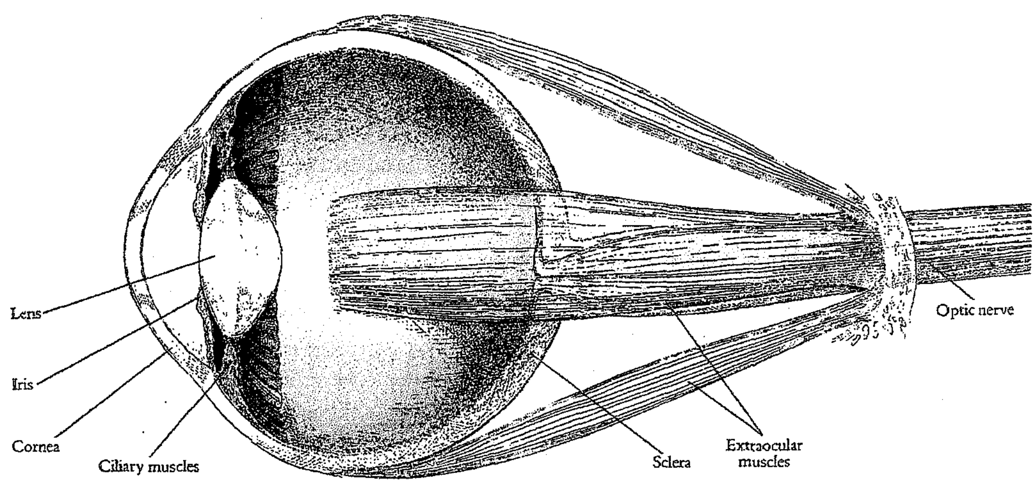


Figure 2. Illustration of the Eye

Source: David H. Hubel. Eye, Brain, and Vision. New York, Scientific American Library. (1987), 34.

Structure of the Eye

The eye is housed and protected in a conical-shaped socket of the skull, called the orbit. It is surrounded with fatty tissue which forms a " ball and socket joint" for eye movement. The eyelids provide protection and keep the cornea lubricated with tear fluid, secreted from the lacrimal glands located at the outer portion of the eyebrow. Tear fluid improves optical quality by filling in the micro structure of the cornea and helps maintain the normal exchange of oxygen and water balance of the cornea (Boynton, 1979).

Eye Movement

Eye movement is controlled by six extraocular muscles. These muscles work in pairs, each pair moving the eye in one of three orthogonal planes (Hubel, 88). Each time we move our eyes, an extremely coordinated contraction and relaxation of these muscles causes a smooth change in eye movement. There are three major types of eye movement: convergence, saccadic, and pursuit. Convergence is the means by which we keep both eyes directed at the same object. Saccadic movements involve a rapid shifting of the point of fixation, as when we are looking for targets, areas of interest, activities, motion, and so forth. The most familiar saccadic movements our eye makes is when we are reading; the eyes remain stationary for about one-quarter of a second, and then make a very rapid movement to a new position. Pursuit movements are relatively smooth movements, used to either pursue an object moving across the visual field or to fixate on an object when we are in motion. These eye movements are very important to vision (Gregory, 1966). If the eye could be held perfectly still, maintaining a stationary image on the

retina, the image would eventually fade. To prevent this, it is necessary for the eyes to constantly shift in a series of micro saccades to slightly reposition the image on the retina so that the receptors do not adapt and cease to signal the brain of the presence of images in the eye.

The Cornea

The cornea is the transparent membrane on the front of the eye where light enters first. It works in conjunction with the lens to focus an image onto the retina. Two thirds of the bending of light required for focusing occurs at the air-cornea interface (Hubel, 1988). The cornea has a refractive index, relative to air, of approximately 1.37. It has no blood vessels, which would degrade its optical clarity, but is densely packed with nerves that function with the eyelids to help protect the eye.

The Aqueous Humor

The aqueous humor is the clear fluid that occupies the area between the cornea and the lens. It provides nutrients to the cornea and is replenished about every four hours. The constant replenishment of this fluid sometimes causes spots, seen hovering in front of the eye, possibly due to floating impurities casting shadows on the retina (Gregory, 66).

The Iris and Pupil

The iris is the colored portion of the eye that controls the amount of light entering the eye through a variable opening, called the pupil. The diameter of the pupil changes primarily as a function of the level of

illumination of the retina. The pupil " limits the rays of light to the central and optically best part of the lens except when full aperture is needed for maximum sensitivity. It also closes for near vision and this increases the depth of field for near objects." (Gregory, 1966). Retinal image quality depends on the size of the pupil. When the pupil is small the image is degraded by diffraction; when it is large the effects of spherical and chromatic aberration are most serious (Boynton, 79).

Diffraction occurs when the incoming light interferes with the edge of the pupil, creating image blur. As the pupil becomes larger, the image blur due to diffraction becomes less. This relates to the fact that opening the pupil allows a smaller proportion of the incoming light being processed by the eye to interact with the edge of the pupil.

Chromatic aberration is the result of varying refractive indexes for a given wavelength. A simple lens always refracts shortwave light more than longwave light, causing chromatic aberration to occur. This is an important problem for color vision and shall be discussed further later.

The iris is composed of loose connective tissue forming the stroma, which is pigmented and gives the eye its color. Within the stroma are two sets of muscle fibers called sphincter fibers and dilator fibers. The sphincter fibers encircle, and on contraction reduce the size of the pupil. The other set of muscles, dilator fibers, extend out radially, like spokes of a wheel and attach to the ciliary body which contains the whole muscle system. Since the dilator fibers are anchored, these fibers open the aperture upon contraction, increasing the size of the pupil.

The Lens

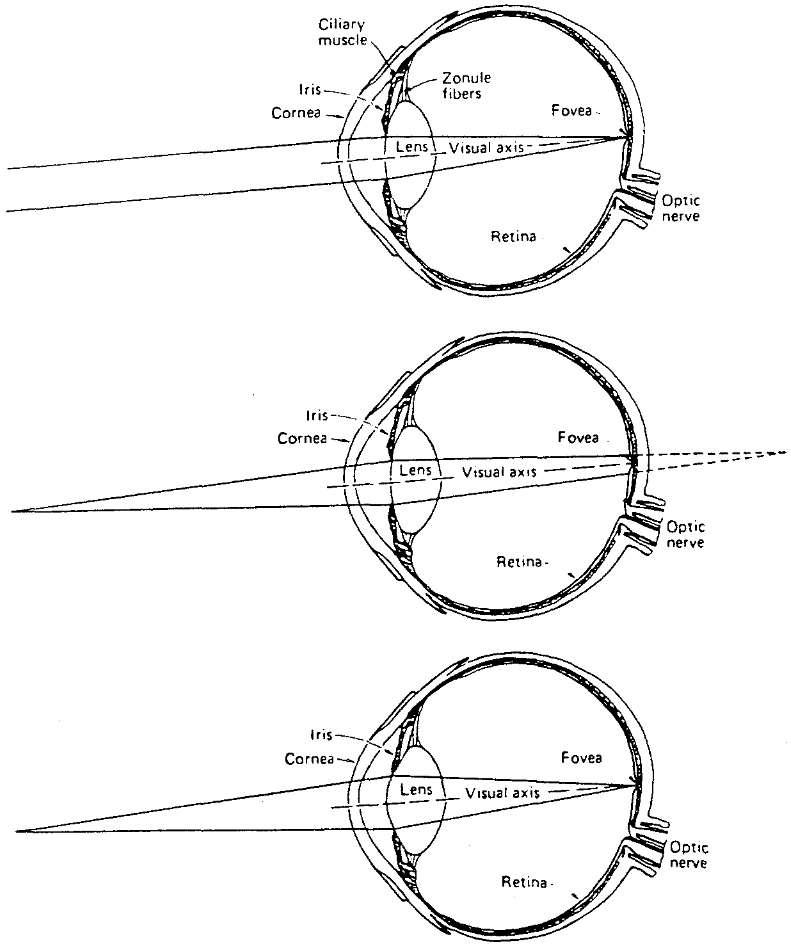
The lens is a clear, rubbery tissue that works in conjunction with the cornea to primarily provide accommodation of near and distant objects. The circumference of the lens is encased by zonule fibers, to which the ciliary muscles attach. When accommodating a near object, the ciliary muscles squeeze the lens making it more spherical or concave. When viewing distant objects, the ciliary muscles relax and the zonule fibers, which are under tension, pull on the lens, thus flattening it. Figure 3 illustrates this action.

The lens is built up from the center in layers, like an onion (Gregory, 1966). The cells in the center of the lens are the oldest. They begin to harden and die beginning around middle age. The hardening of the lens makes it difficult for the ciliary muscles to squeeze the lens to accommodate near objects. This creates a condition known as presbyopia, or farsightedness, hence, the need for reading glasses. The lens continuously develops throughout life, but ironically it begins to grow old even before we are born.

The Retina

The retina is the light sensitive portion of the eye and comprises approximately two-thirds of the inside surface of the eye. The complexity of the retina is realized from this description by Gregory (1966):

"The retina has been described as an outgrowth of the brain. It is a specialized part of the surface of the brain which has budded out and become sensitive to light, while it retains typical brain cells lying between the receptors and the optic nerve (but situated in the front layers of the retina) which greatly modify the electrical activity from the receptors



"**Top:** The lens of the eye is held in a flattened position by the action of the zonule fibers that support it. Light from a distant source provides parallel rays, seen entering from the left. The cornea provides most of the refraction needed to bring the rays to a sharp focus at the fovea. **Middle:** The fixated object has been brought close to the eye. The shape of the lens has not changed, and the refraction at the cornea is no longer sufficient, because the rays striking it are now divergent, to form a point image on the retina. Instead, a circle of light intersects the retina and the image is blurred. If a hole were cut in the back of the eye, an image would be formed behind it, as shown by the dotted lines. **Bottom:** Contraction of the ciliary muscle releases some of the tension of the zonule fibers. This is the act of accommodation. The lens changes shape, especially at its anterior surface. This added refractive power is now sufficient to restore a sharp image at the fovea."

Figure 3. Accommodation of Near and Distant Objects

Source: Robert M. Boynton. Human Color Vision. New York: Holt, Rinehart, and Winston. (1979), 78.

themselves. Some of the data processing for perception takes place in the eye which is thus an integral part of the brain."

The retina consists of multiple layers of nerve cells and a layer of two types of cells called rods and cones, named so because of their shapes. Together the rods and cones constitute the photo receptors that translate light energy into nerve impulses. The rods and cones are the farthest removed from the light entering the front part of the eye. Light must first pass around the nerve cells, strike the rods and cones, and then pass through the nerve in order to generate nerve impulses (see figure 4).

The rods are used primarily for peripheral vision and night or low intensity light vision. They are placed mostly in the periphery of the retina and are only capable of perceiving in black and white. The rods are approximately one thousand times more sensitive to light than cones.

The cone cells are used primarily for daylight vision or high illumination. The cone cells are capable of perceiving color. Cones are dispersed throughout the retina. However, most of the cones are concentrated in an area of the retina called the fovea, meaning pit. This is the region of the retina where greatest visual acuity is achieved. It is the density of cones in the fovea that allow for the resolution of fine visual detail. There are about 150,000 cones per millimeter squared in the central fovea which is the highest concentration of cones anywhere on the retina (Boynton, 1979).

There are some imperfections inherent to the makeup of the retina that are very pertinent for aviators. The area where the optic nerve attaches to the retina is void of any rods or cones. This creates a "day blind spot", but is overcome because of binocular vision. Another inherent deficiency of the

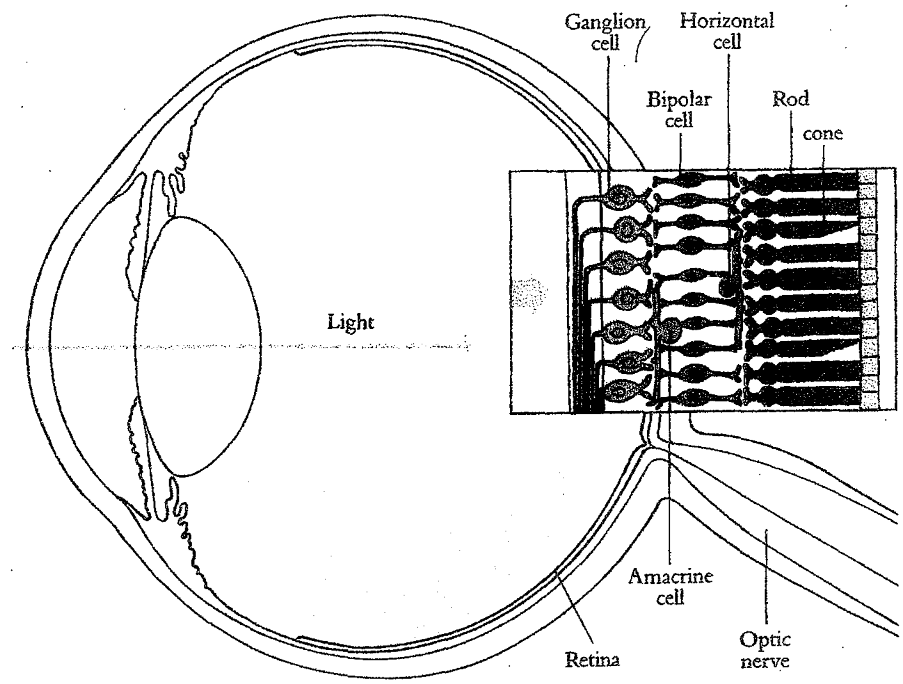


Figure 4. Path of Light to the Rods and Cones

Source: David H. Hubel. Eye, Brain, and Vision. New York, Scientific American Library. (1987), 37.

retina is because the fovea is packed exclusively of cones, they become ineffective under low light levels. This results in poor resolution of detail. Visual acuity decreases to 20/200 or less, which means what you can normally read at two hundred feet decreases to twenty feet. Because the fovea is packed exclusively of cones a "night blind spot" is created, which requires off-center viewing in order to see an object at night. If a person attempts to view an object straight on at night, they will notice that the object disappears due to the effects of this night blind spot. It is the rod cells that are used for night vision.

Detection of Light

There are chemical substances in the rods and cones, called visual pigments that detect light. There are four types of visual pigments, three for cones and one for rods. Rod pigment, or rodopsin, is the most understood of all the pigments. It is the only visual pigment to be extracted from the eye for study. Rodopsin is composed of two parts: a protein molecule called opsin and a molecule made from vitamin A called retinene. When light strikes rodopsin, the retinene portion is split away or bleached from the opsin portion. This leads to nerve inputs, by a mechanism that is still unclear, that relay visual information to the brain (Grolier, 1994). In the dark, and with the aid of chemical energy obtained from metabolism, retinene and opsin are recombined and rhodopsin is reconstituted. In very intense light, the rhodopsin may split faster than it can be reconstituted. In this event, vision may become impaired, for example as in snow blindness or when staring directly into the sun.

It is believed that the visual pigments for the cones work in much the same way, but at different wavelengths of light. More will be discussed about cones in the next section.

Chapter 3

Human Color Vision

The subject of color vision has been studied by some of the most brilliant men who dedicated their lives to science and knowledge. Nevertheless, color is still poorly understood even by artists, physicists, and biologist because of its extreme complexity.

Sir Isaac Newton was the first great mind to study color vision. He wrote a classic book on the subject titled *The Opticks* which may be "the scientific book of its period most worth reading today" because it lays the basic foundation of the knowledge of color (Gregory,1966). It was Newton who proved that white light is composed of all spectral colors using his prisms.

Since Newton's study of color vision, there have been many theories submitted on the subject. Of all the theories, the Young-Helmholtz theory is most accepted, and the one acknowledged for this thesis. Before continuing, it is important to concentrate on light as wavelengths because "it is this property that is the stimulus for color perception" (Haber, 1975). Additionally this paragraph from Huble's *Eye, Brain, and Vision* (1988), illustrates the different disciplines of science needed to study and understand color vision:

"In thinking about color, it is useful to keep separate in our minds these different components: physics and biology. The physics that we need to know is limited to a few facts about light waves. The biology consists of psychophysics, a discipline concerned with examing our capabilities as instruments for detecting information from the outside

world, and physiology, which examines the detecting instrument, our visual system, by looking inside it to learn how it works. We know a lot about the physics and the psychophysics of color, but the physiology is still in a relatively primitive state, largely because the necessary tools have been available for only a few years."

The Young-Helmholtz Theory of Color Vision

An essential problem for the eye is the ability to get a neural response for different light frequencies. Frequencies in the visible spectrum are far higher than what the nerves can follow directly. The highest number of impulses a nerve can transmit is just under 1000 cycles per second. The frequency of light is a million cycles per second (Gregory, 1966). If there was a cone cell for every color, there would have to be over four hundred kinds of cones. Given the current size of a cone cell, there physically wouldn't be any room on the retina to place all the receptors. Thomas Young (1773-1829) investigated this issue and in 1801 wrote this (Gregory, 1966):

"As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation it becomes necessary to suppose the number limited for instance, to the principle colors red, yellow and blue..."

He later changed the three principle colors to red, green, and violet which are referred to today as red, green, and blue. It was also Young who suggested that all the colors of the spectrum could be attained by mixing the three principle colors. The idea that any color could be produced by manipulating three controls was termed trichromacy. Herman Helmholtz, a brilliant man, championed Young's theory, adopted it, and continued research on the subject.

It was Helmholtz who explained the differences in mixing of paints versus the mixing of light to produce color. Mixing paints is physics. Mixing light is biology (Huble, 1988).

The Young-Helmholtz theory states that there are three principle colors: red, blue and green; and three types of color sensitive cone receptors in the retina, with all colors being visible by a mixture of signals from these three systems (Gregory, 1966). By mixing red, green, and blue light you can attain any color in the spectrum. However, there are some colors visible that aren't in the color spectrum. Gregory writes in reference to this observation:

> "Color vision is extremely complicated, for instance; the color brown is not in the spectrum but we do see brown. This is an example that color depends not only on the stimulus wavelengths and intensities but also on whether the patterns are accepted as representing objects, and this involves high level processes in the brain which are extremely difficult to investigate."

The Young-Helmholtz theory was confirmed in 1959, when a group of scientists examined microscopically the abilities of single cones to absorb light of different wavelengths and found three cone types. The initial basis for color perception, therefore, lies in the relative rates of light absorption by the three cone types, just as Thomas Young suspected long ago.

Cones

Each of the three types of cones contains a visual pigment that absorbs some wavelengths of light better than others. The properties of these pigments are believed to react similarly to rhodopsin in the rods. It is important to note that the visual pigments of the cones have not been

successfully extracted, so the mechanism by which they work is still simply theory. It is believed that the visual pigment absorbs a photon of light and changes its molecular motion, releasing energy. This release of energy creates an electrical signal which travels through the various nerve cells of the retina and to the brain. It is the brain that interprets these signals as color.

The pigments of each cone type has a peak absorption wavelength as do the rods. The "blue" cones peak sensitivity is about 430 nm, the "green" cones peak is about 530 nm, and the "red" cones peak is about 560 nm. The blue, green, and red designation for the three cone types is simply a label, and does not reflect the color of the peak absorption wavelengths. In actuality, the monochromatic light with wavelengths at 430 nm, 530 nm, and 560 nm would be seen as violet, blue-green, and yellow-green respectively (Huble, 1988). The rods peak sensitivity is at about 510nm but the chemical processes of the rhodopsin is such that only achromatic (grays and blacks) light is perceived. Figure 5 illustrates the sensitivity curves for the three different types of cones.

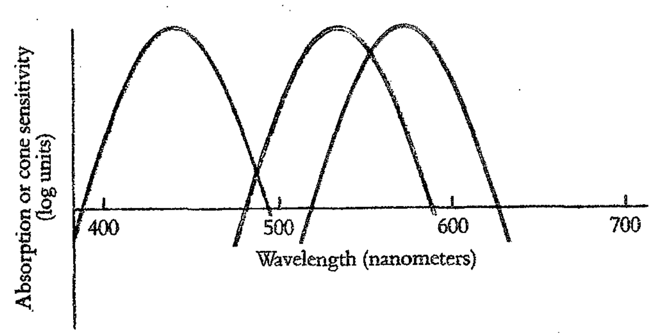


Figure 5. Peak Sensitivity Curves for the Three Types of Cones

Source: Hubel, David H. Hubel. Eye, Brain, and Vision. New York, Scientific American Library. (1987), 163.

The curves indicate that there is an overlap between the cones, which is essential in order to perceive all colors of the spectrum. This explanation of the operation of the cone and rods is an important concept that is the foundation of the hypothesis of this thesis which is that retinal physiology pertains to color selection of heliport approach lighting systems.

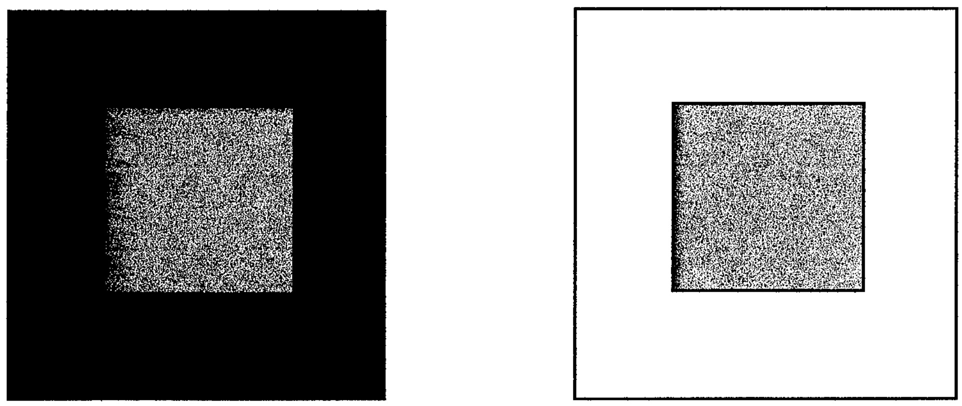
Brightness and Contrast

Brightness and contrast play an important role in how color is perceived. Understanding the effects of brightness and contrast can influence the actual design of helipad lighting systems.

Brightness is the simplest of the visual sensations. Brightness is not simply the intensity of the light source, though it is often confused with intensity. Brightness depends on the state of adaptation of the retina along with other complicated conditions. Intensity is the physical energy of light which can be measured. Brightness is an experience. If light of different colors, but the same intensity is shined into the eyes, colors at the middle of the spectrum will look brighter than those at the ends.

A light source is seen by virtue of its contrast in brightness and/or color with the background against which it is viewed (SAE, 1970). Contrast can be described as an enhancement, or intensification, of perceived differences between neighboring colors. Simply put, contrast makes objects stand out more prominently from their surroundings, hence a perceived difference in brightness. For example an area surrounded by a darker color appears brighter. This effect is illustrated in figure 6 in which the two green areas

have the same reflectance, although the one enclosed by the black appears brighter than the other.



The two square green areas have the same reflectance although the one enclosed by the black appears brighter.

Figure 6. Demonstration of Brightness and Contrast

One can see how these specific effects of color need to be considered for the background environment for which a helipad lighting system will operate. The eye's ability to detect an object depends upon the contrast between the apparent brightness of the object and the apparent brightness of the background. In a worst case scenario, the background environment could wash out the primary approach lighting. The color selected for the lighting system must contrast positively.

Chapter 4

Imperfections of the Vision System

Current airfield lighting systems are illuminated with many different colors to provide specific cues for aiding pilots. However, some researchers question whether or not there are too many colors, suggesting that there might be instances of overdesign with negligible benefits or even counter-productive results. Some of these counter-productive results are due to the lack of knowledge, on the designer's part, of the inherent deficiencies of the eye.

Understanding the deficiencies of the visual system is important when designing a new approach lighting system so that these effects are not worsened. The effects of aging and certain wavelengths of light create focus and depth perception problems which could obviously cause pilots considerable difficulty.

Color Blindness

Color blindness occurs when there is a deficiency in one or more of the cone systems. The most common color confusion is between red and green. Less common is green-blue confusion. Green cone deficient people perceive color in shades of yellow and blue. A deficiency of the red cones decreases the ability to distinguish reds and oranges. Among those with color deficiencies, those with red deficiencies usually do worse than those with green deficiencies

(Sanders, 1993). Almost ten percent of men are color deficient, whereas color deficiencies in women are rare (Gregory, 1966).

As we grow older, our ability to perceive color at the extremes of the visual spectrum decreases due primarily to the aging effects of the eye's components. Current regulations allow people with certain color deficiencies to be licensed to fly, but with restrictions on night flying. There have been studies conducted to determine if the extensive color coding used in aviation is necessary. These studies have concluded with recommendations for designing future systems, selecting colors for color recognition tasks, and the introduction of devices for information (numbers, patterns, etc.) (Watkins, 1971). Most people who are colorblind cope just fine in everyday life by developing alternative methods of distinguishing colors based on environment, location, and orientation.

Presbyopia

Presbyopia, or farsightedness, is a condition where the cells at the center of the eye's lens harden and the muscles of the lens atrophy. The lens can no longer conform to the shape necessary to focus a close object onto the retina. As the lens thickens it yellows and reduces the transmission of blue light through it. This condition begins around age forty, making instruments, maps, newspapers, books, and checklists more difficult to read as the condition worsens. This difficulty can be corrected with bifocal spectacles which compensate for the inadequate accommodative power of the eye's lens.

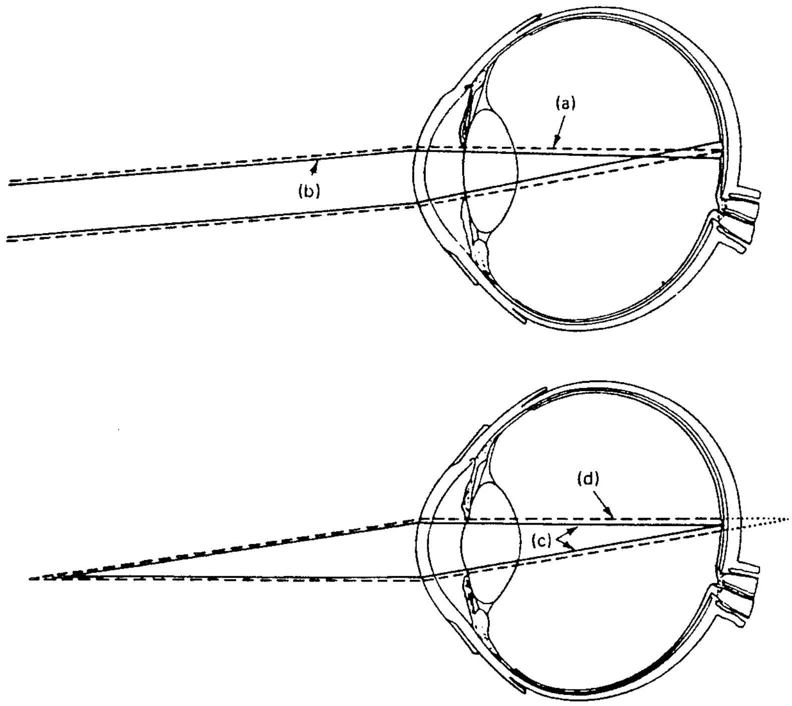
Myopia

Myopia, or nearsightedness, is a condition caused by an error in refraction in which the lens of the eye does not focus an image directly on the retina. The distant image being viewed is focused in front of the retinal plane. This causes blurred vision, with distant objects not being seen clearly; only near objects are in focus.

At night blue wavelengths of light prevail in the visible spectrum. Because of this, slightly nearsighted people will experience visual difficulty at night when viewing blue light which could cause blurred vision. This condition can be corrected easily with spectacles.

Chromostereopsis

Chromostereopsis is a phenomena which comes about from the chromatic aberration of the eye, discussed earlier. This phenomenon creates a false depth perception when color pairs from opposite ends of the visual spectrum are placed together such as red and blue and to a lesser extent, red and green. For example, if the eye is focused on a red target of 700nm, a blue target of 400nm at the same distance will be out of focus. In general, colors at the extreme ends of the spectrum are not good for the eye in terms of chromostereopsis regardless of whether they are paired. The eye tends to focus the blue wavelengths on the front of the retina and the red wavelengths behind the retina (see figure 7).



"Chromatic aberration in the eye. Distant targets can never be in focus for violet light (b). Near targets can be (c), but not simultaneously for red light (a) (d)."

Figure 7. Chromostereopsis

Source: Robert M. Boynton. Human Color Vision. New York: Holt, Rinehart, and Winston. (1979), 67.

To counter the effects of chromostereopsis when designing a lighting system, it is important to avoid using the extremes of the color spectrum, the reds and blues and to a lesser extent, red and green, or blue and green on a dark background (Sanders, 1993).

Visual Illusions

Illusions give false impressions or misconceptions of actual conditions. Decreasing visual information will increase the probability of disorientation for pilots. Although the visual system is the most reliable of the senses, some illusions can result from a misinterpretation of what is seen.

Spatial disorientation can be induced from many types of light sources, including strobe lights, flares, and vehicle lights (Schmidt, 1996). Some aviators have confused certain geometric patterns of ground lights, such as moving trains, with runways and approach lights. There have also been incidences where pilots have confused ground lights with the stars and placed their aircraft in dangerous unusual attitudes.

External Factors Affecting Color Perception

There are several external factors that affect a pilot's color perception. Sunglasses can alter the spectral transmittance of light, which changes the color of a viewed object. For example, the U.S. Army has banned the use of sunglasses with plastic lenses because they alter the transmittance of amber colored light. This came about after instances of pilots' inability to recognize the amber caution/warning lights in the cockpit. Since color perception may already be reduced by the tinted windows of some aircraft, it is important

that no further reduction is imposed by sunglasses. Additionally, tinted windows in the cockpit of an aircraft can cause a reduction in contrast of low-luminance objects outside the aircraft at night.

Another external factor to consider is the light source itself. In any light source the color emitted will vary with time due to aging of the lamp, differences in the voltage supplied and weathering of the filter. Differences in voltage can change the color output of the lamp, while the weathering effects of plastic lamp lenses can "yellow", changing the spectral transmittance of the light. If these lighting systems are not properly maintained, the slight differences in hue presented to pilots could cause visual illusions. For example, if the runway lights are brighter on the right side of the runway than on the left side an illusion is created causing the pilot to bank the aircraft to the right (Schmidt, 1996).

There are many factors that can deceive our visual system. Only a few of the obvious factors have been discussed in this chapter. Unfortunately, little has been done in the last twenty years in making engineering changes to lighting systems to reduce some of these deleterious effects.

Chapter 5

The Best Color for Helipad Lighting

Since much is now known about how the eye works, selecting a color for primary heliport lighting is simply a matter of determining a wavelength of light that enhances the eye's performance for the given visual task.

Perjenke Effect

Based on the physiological and the psychophysical study of the eye, light at a wavelength of approximately 525 nanometers is the best color for primary helipad lighting. The color at this wavelength is green-blue. At this wavelength, both the rods and cones are stimulated to approximately 85 percent of their peak sensitivity. The curves in figure 8 illustrate the peak luminosity (which is directly related to sensitivity) of the cones (a) and the rods (b). The intersection of these two curves is important because it is a point where all four types of photo receptors are performing at a high level of sensitivity. With this number of photo receptors working in both the foveal and peripheral areas of the retina, visual acuity is enhanced and the visual search time to acquire a light source is reduced.

The graph in figure 8 shows that the eye is not equally sensitive to all wavelengths of light. The selection of 525 nm is a compromise, in that it is a good color for both day and night environments. At light levels of three candela and above, the rods and cones are both functioning and the eye is most sensitive to wavelengths at approximately 550 nm (green). As

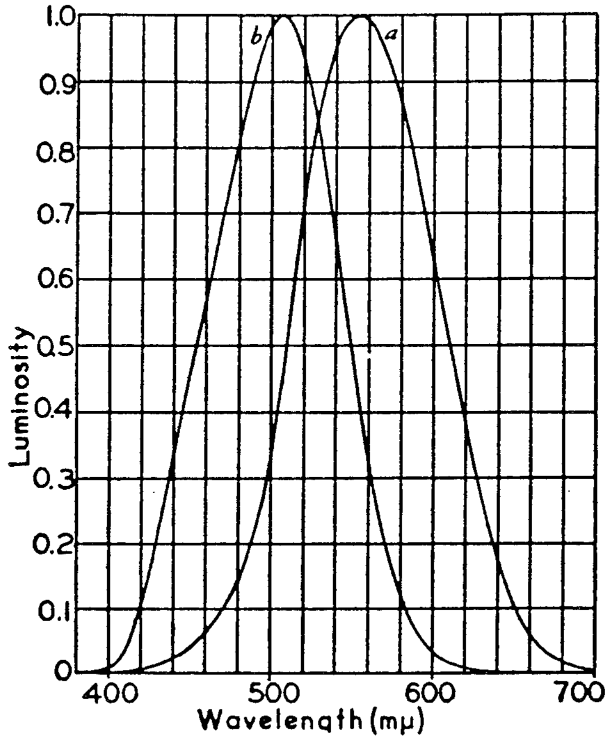


Figure 8. Rod and Cone Sensitivity Curves

Source: Optical Society of America. The Science of Color Committe on Colormetry. Washington D. C.: Optical Society of America. (1970), 225.

illumination levels decrease, the cones become less sensitive and the rods take over the primary vision task and the eye becomes most sensitive to wavelengths around 500 nm (blue-green). This shift in sensitivity from cone vision (day vision) to rod vision (night vision) is called the Purkinje Effect.

Physiological Enhancements

A heliport located within a city is considered the "worst case" environment for heliport lighting because of all the distracting lights that compete with the heliport lighting. The green-blue color will contrast well with the yellow hue of the sodium lights that are ever present in a city. This positive contrast creates an effect called phototropism where the eye naturally turns towards the light source. Also, the color difference between the proposed color and the background lighting should be discriminable across the entire retina, resulting again in quicker acquisition time.

The focusing capability of the eye is optimized for wavelengths in the middle of the color spectrum. Using the proposed green-blue wavelengths of light increases visual acuity because of the reduced effects of chromatic aberration. Additionally using this color of light eliminates the effects of chromostereopsis because the approach lighting array would be entirely made up of this green-blue light.

Other Color Considerations

There are other areas of a heliport that will require lighting for such things as marking hazards, taxiways and parking areas. Color conventions currently in use could still be used for these areas, however there are certain

design considerations that must be taken into account. Red lighting will always be used to mark hazards, but for heliports, red lighting incorporated within the approach lighting, or primary helipad lighting, should be avoided because of the posibility of inducing chromostereopsis.

The eye is very sensitive to amber light. It has a tendency to overpower and washout the green-blue lighting if it is placed within the green-blue lighting array. If amber lighting is used, the designer must place the amber lighting in such a way that it does not affect the green-blue lighting.

The blue color currently used for taxiways should be avoided in future designs because of the adverse effects that this short wavelength light has on the eye. It has been found that the normal eye focuses blue images in front of the retina, and accomodative adjustments may not be sufficient to bring blue images into clear focus (Silverstein, 1985).

Finally, the designer should limit the number of different colors used for a heliport lighting layout which will reduce the liklyhood of creating a "sea of lights" effect.

Chapter 6

Testing

The central approach to testing the application of relevant information about human color vision was by conducting flight evaluations to an experimental helipad approach lighting array. Under the conditions of the test, subjective responses were the only reasonable method for measuring the criterion of interest which was to obtain pilot responses to the color of the lights.

Test Method

Five pilots were used for the flight evaluations. Flight experience averaged 3400 total flight hours with a high time of 6000 flight hours and the low time of 1200 flight hours. All but one pilot were military trained helicopter pilots. The professional experience of the subject pilots consisted of one experimental test pilot, two pilots with aviation research and development experience and two pilots with operational experience.

The flight evaluations were conducted at night using a Bell 206 Jet Ranger helicopter. The weather conditions for the entire test period were clear skies and unrestricted visibility with zero moon illumination.

Each pilot conducted four visual approaches. The subject pilots tasks where simply to acquire the helipad from approximately 1.5 miles, conduct a

normal approach and safely terminate the flight at the helipad. A safety pilot and observer accompanied each subject pilot.

Lighting Configurations

Three types of lighting technology were used to evaluate the green-blue color. The helipad diagram in figure 9 shows the general lighting configuration tested that utilized all three types of lighting technology. The point source lights were cold cathode ray type lights that emitted light at 518 nm. The light pipe, essentially a large fluorescence light, transmitted light at 507 nm. The electro-luminescence panels transmitted at approximately 530 nm. These panels were used to form the "H" in the center of the landing area.

It is important to note that all the lighting technology was off the shelf equipment donated by various manufacturers. Consequently it was impossible to obtain lighting that could transmit light at the desired wavelengths for testing. Most manufacturers do not have an in house capability to measure the color performance of their systems. However, the lights used for this test proved to be exceptional in achieving the desired effects for this test.

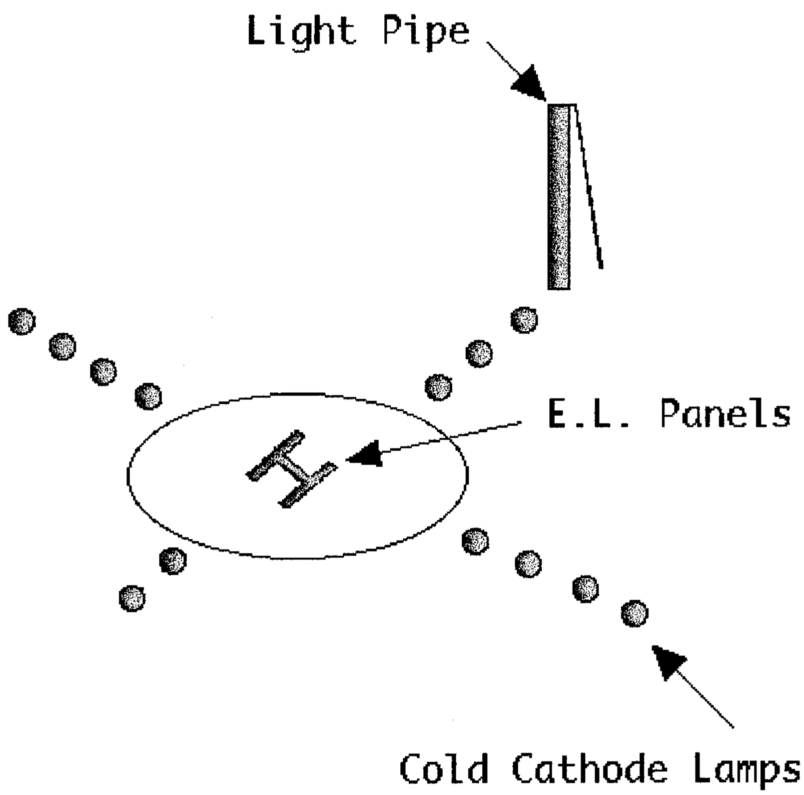


Figure 9. Diagram of Helipad Used for Testing

Test Results

Pilot opinion of the green-blue color was very positive. All of the subject pilots agreed on the following points:

- The color of the lights is unique and easily identifiable. The green-blue color makes the pad more distinguishable.
- The green-blue color is very comfortable to view.
- The green-blue color coupled with the lighting configuration provides clear information, such as pitch and roll cues.

<u>Chapter 7</u>

Conclusion & Recommendations

The rapid changes in the air navigation system demand that system planners design new approach lighting systems for heliports that provide effective information to the pilot for course guidance, terminal cues, and ground identification. It has been established that the inherent flaws of the human vision system contribute to perceptual illusions and other visual problems, creating misinformation to the pilot.

Conclusion

The research and testing at UTSI has shown that a well designed lighting configuration coupled with lighting color that is optimized to the physiological capabilities of the retina can provide excellent visual cues without overloading the pilot with redundant, useless or confusing information. The green-blue color at approxmiately 525 nm is the best color for primary heliport lighting for the following reasons:

1. The green-blue contrasts well with the background lighting generated from a city.
2. Vision performance is enhanced by increased visual acuity and reduced visual search time.
3. Several visual illusions are eliminated.

This research has generated interest from lighting manufactures and the FAA. The FAA has accepted the idea that color will be an important consideration for future approach lighting systems. Reynold Schmidt MD., vice president of Light Beams and participent in this research, has written several papers on spatial disorientation caused by airport lighting systems and agrees with the hypothesis that retinal physiology is key for the proper selection of heliport lighting (Schmidt, 1996). The positive responses by the subject pilots, and the interest shown by the FAA and industry indicates that the scientific selection and application of color to heliport approach lighting systems is the right approach for future designs.

Recommendations

More testing is needed to ensure that the proposed green-blue color provides the required visual information under various conditions. Below is a list of recommended follow on testing:

- Conduct testing under actual instrument weather conditions, both day and night.
- Conduct testing at an actual heliport located on a roof top in a city environment.
- Conduct testing on helipad contrast to make the landing area more visible.
- Test for Night Vision Goggle compatibility.

- Conduct test to compare pilot's perceived flight path with the aircraft's actual flight path

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Craig Ernst [redacted], [redacted]. He attended three years of high school overseas at Kaiserslaurtern American High School in Kaiserslautern Germany. He graduated from Highland High School, Albuquerque New Mexico in May of 1979. On July 23, 1980 he entered the U.S. Army Warrant Officer Flight Training Program and began a career as an Army Aviator. He graduated honor graduate from flight school on September 18, 1981 and was selected to fly AH-1 Cobra Attack Helicopters. His first assignment was to the 7/17 Cavalry Squadron, Fort Hood Texas. In September of 1985 he was selected to fly the AH-64 Apache and was one of the Army's first operational AH-64 Apache pilots. On August 22, 1988 he earned an Associate Degree in Applied Science from Central Texas College. While assigned to the 2-227 Aviation Regiment in Hanau Germany, he was deployed to the Persian Gulf on December 29, 1990. There, he saw combat and fought the Tawakalna Division of the Iraqi Republican Guard destroying 11 armored combat vehicles. After returning from Desert Storm he completed his undergraduate studies and was awarded the Bachelor of Science in Professional Aeronautics, Cum Laude, from Embry Riddle Aeronautical University on January 30, 1993. In April of 1995 he was selected for the Army Engineering Test Pilot Program with assignment to the University of Tennessee Space Institute to pursue a Master of Science Degree in Aviation Systems. His military decorations include two Bronze Stars, one with "V" device, three Meritorious Service Medals and one Air medal. He is married to Lorraine and has two sons, Joshua and Trent.